**Decision support capability** will integrate the data analysis, the diagnostics, the offline history, and piece-part pedigree information to determine if the condition is a known failure mode or something that is not fully understood. Today this activity requires human operators with years of experience to research and pull together all the pertinent data. Incompatible databases and manually recorded log notes prevent the full automation that can make advanced reasoning capabilities possible.
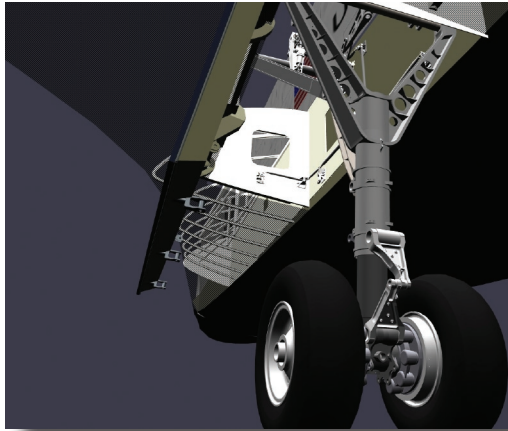

System simulation that combines the physical data with the model environment to make inferences about aspects of the system is needed to augment real-time analysis capabilities. Today this capability is limited by processing power, fidelity of the simulation environment, and the validation/certification of the modeled system. All of these capabilities will benefit from standard software interfaces that allow the output of one capability to drive one or more additional analysis tools.

The integration of the real-time data and various offline workflow processes (Problem Reporting and Corrective Action; Work Authorization Document generation, approval, and execution; logistics; work scheduling; and flight readiness determination and documentation) is needed to achieve a truly electronic workflow. Sharing this information back and forth has some technological challenges, such as interfacing with existing legacy workflow systems without modifications; integrating nonautomated workflow processes seamlessly into the automated process; and providing security and authentication capabilities for communication into the real-time environment.
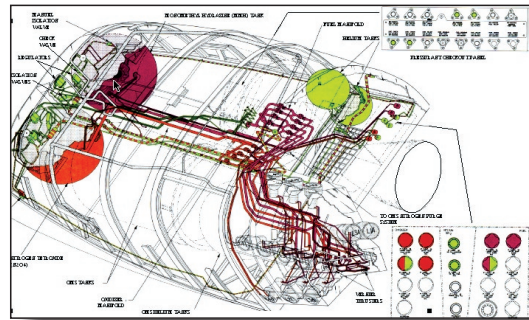
Command authority should reside where it logically applies and not in an arbitrary centralized location. As an example, a spaceflight vehicle requiring automated and integrated servicing at the spaceport would be the command authority for the integrated operation. The vehicle could request services from the spaceport, provided that such services would not jeopardize the safety and security of the spaceport. Differences between spaceflight vehicle hardware and spaceport hardware would be abstracted into a standard software interface that hides the hardware details. A service discovery capability would query across the spaceflight vehicle/spaceport interface to determine what capabilities are available and to satisfy the abstract interface with a concrete realization.
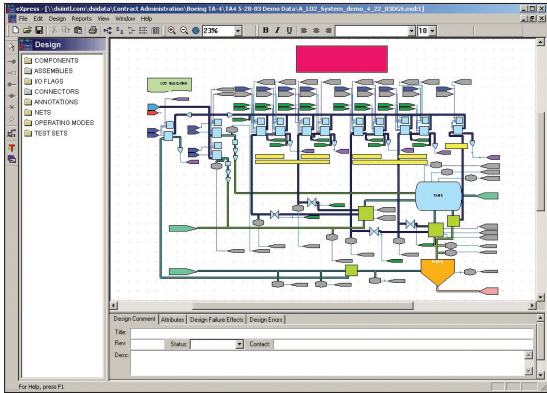
Automated software verification and validation is the single technology element that affects all aspects of CCM. The advanced intelligent software that is needed to make this spaceport vision a reality will require verification and validation techniques that are beyond what we have traditionally used. Today we identify critical areas and develop test cases to run through the software and cover as many paths as possible. Formal techniques and additional automated capabilities to test the software continuously during the development cycle and into the verification and validation phase are needed to verify coverage of all paths. This automated verification needs to be used to regressively test the software when other system software changes, such as operating system upgrades or system patches. Verification and validation of these advanced software capabilities will be the limiting factor in what we can accomplish toward this vision.

The CCM technology elements are summarized in Table 22.

Table 22. CCM technology elements

General	• Standard hardware interfaces • Standard software interfaces • Automated service discovery for configuration determination and reconfiguration
Monitor	• Wireless sensors • Sensor packaging, connectivity, and protocols • Inherent sensor connection integrity validation • Multiparametric measurements and sensors • Distributed intelligent/fault-tolerant sensor systems • Health management and integrated monitoring systems • Advanced hazards detection • Advanced communications – microwave and laser • High-volume/speed processing, storage, and display technologies • High-performance analog-to-digital converters • Improved precision time sources • Data visualization and fusion • High-speed flexible networks • Advanced data storage and retrieval systems
Assess	• Decision support tools and collaborative decision-making tools • Intelligent software agents and expert systems • Human system interfaces for decision making • Information assurance • Prognostic health determination • Adaptive reasoning advisors
Plan	• Condition-based maintenance • Dynamic planning and execution • Automated planning • Modeling and simulation • Automated resource tracking and configuration control
Execute	• Autonomous command and control with distributed command authority • Human and computer interaction and team dynamics • Multimodal command chain communication • Adjustable levels of autonomous operations • Encryption technologies • Multilevel security

CCM Technologies Roadmap

Figure 37 displays the major technology areas, with time-phased recommendations regarding particular technologies to pursue in improving the ability of spaceports to perform the Command, Control, and Monitoring function.
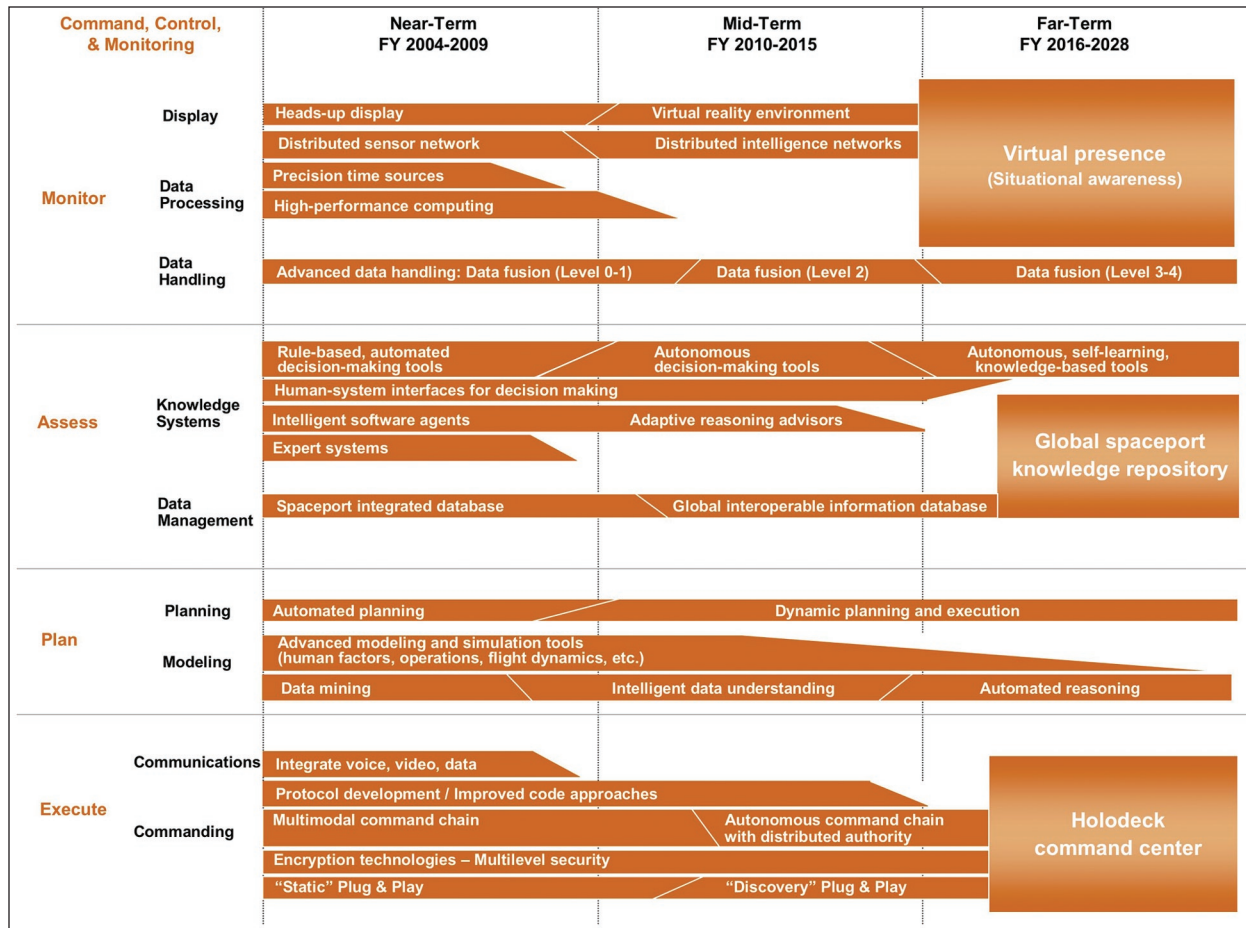

Command, Control, & Monitoring		Near-Term FY 2004-2009	Mid-Term FY 2010-2015	Far-Term FY 2016-2028
Monitor	Display	Heads-up display	Virtual reality environment	**Virtual presence** (Situational awareness)
		Distributed sensor network	Distributed intelligence networks	
	Data Processing	Precision time sources		
		High-performance computing		
	Data Handling	Advanced data handling: Data fusion (Level 0-1)	Data fusion (Level 2)	Data fusion (Level 3-4)
Assess	Knowledge Systems	Rule-based, automated decision-making tools	Autonomous decision-making tools	Autonomous, self-learning, knowledge-based tools
		Human-system interfaces for decision making		
		Intelligent software agents	Adaptive reasoning advisors	**Global spaceport knowledge repository**
		Expert systems		
	Data Management	Spaceport integrated database	Global interoperable information database	
Plan	Planning	Automated planning	Dynamic planning and execution	
	Modeling	Advanced modeling and simulation tools (human factors, operations, flight dynamics, etc.)		
		Data mining	Intelligent data understanding	Automated reasoning
Execute	Communications	Integrate voice, video, data		**Holodeck command center**
		Protocol development / Improved code approaches		
	Commanding	Multimodal command chain	Autonomous command chain with distributed authority	
		Encryption technologies – Multilevel security		
		"Static" Plug & Play	"Discovery" Plug & Play	

Figure 37. Command, Control, and Monitoring technologies roadmap

5.4 Inspection and System Verification

Inspection and System Verification is performed to ensure a system will perform as required.

Description

The role of Inspection and System Verification is to determine and verify the level of confidence that components, elements, subsystems, and integrated systems will perform as designed to satisfy the following objectives:

- Certify flight elements are ready for flight
- Ensure safety, system confidence, and structural/functional integrity of flight elements and critical ground systems

Achieving these objectives ensures successful vehicle operations and public safety for each mission. Assurance of these conditions is obtained through inspections and comprehensive testing of systems. Because of the diverse nature of the vehicles and hardware supported by the spaceport, a variety of test and inspection scenarios must be accommodated.

Challenges

Inspections are often performed as a direct result of not having confidence in the design of vehicle/payload systems. Procedures often require ground crews to "break" a system to determine if the system is broken. Often the inspections are intrusive, requiring access to hard-to-reach locations and the installation of ground support equipment (GSE) platforms. In addition, the technicians may have to interrupt or dismantle other systems to access the suspect system, which in turn may require additional inspections, checkouts, and system verifications. The more access required and the more systems that need to be dismantled/interrupted, the greater the chance of collateral damage.

Inspections are most often accomplished either visually or via specialized instrumentation and regularly require extensive use of resources. These resources are generally manifested as time and labor, thereby making spaceport operations less efficient and ground service more expensive. Future spaceport operations concepts look to perform inspection and system verification functions by using three major methods: predictive maintenance (using data and tracking trends to predict potential problems), extensive reliance on integrated health management, and manual visual/physical inspections. Historically, labor has been the cost driver for ground operations. It is the strategic investment, development, and application of integrated health management technologies combined with improved predictive analysis tools that will allow for the reduction of manual visual/physical inspections, thereby reducing/minimizing the costs associated with the labor currently required to perform these functions.

Inspection and System Verification faces challenges in meeting the performance requirements of the Plug & Play model. Three sets of challenges exist: integrated health management systems, sensors, and analysis tools. These challenges pose specific concerns in meeting the needed performance. Table 23 summarizes these set of challenges.

Table 23. Inspection and System Verification challenges

TFA Function	Challenges

Integrated Health Management Systems	• Sensing, understanding, and testing the health of the vehicle and ground systems
	  – Complex, redundant, and intrusive
	  – Manual process, subject to error, and may result in damage in the process
	  – Limited access
	  – Uses unique acceptance and inspection criteria
	  – Humans operating in a hazardous environment (e.g., weather, hazardous commodities)
	  – Too many inspections, checkouts, and retests are performed in critical path
	  – Too many interfaces
	  – Inspection, isolation, repair, checkout, and verification are labor-intensive
	  – Risk adverse environment
	• Integrate the IVHM/IPHM/IGHM* data
	  – Verify the data from the IVHM/IPHM/IGHM are all meshing
	  – Have access to all procedures, drawings, etc.
	  – Human in the loop and with maximized use of automated tools for analysis
	  – Vehicle (specific tail) historical maintenance records
	  – Universal, standardized approach
	  – Knowledge management
	• Reliability of overall health monitoring system has to be greater than the flight system
	  – Being able to tell when a sensor is going out of whack
	  – Being able to tell if in a fly/don't-fly situation
	  – Needs its own flight commit criteria
	  – Needs a health monitoring system for the health monitoring system

Sensors	• Reliability of sensors/instrumentation
	  – Sensor failures
	  – Calibration of sensors
	  – Nonrobust sensors
	  – Sensors are part of the component; need to replace components because the sensor is part of component
	  – Sensor reading verification
	• Connecting sensors to the analysis tool
	  – Interference from other systems

Analysis Tools	• Making sense of a lot of data • Data cross talk • Minimizing interpretation • Programming in intelligence – need the right intelligent models • Determining overall system performance is impacted by loss of a sensor – determine how well system can function even when a sensor fails • Finding the problem and resolving the problem • Digging for further details • Finding procedures to resolve the issues
*IVHM: integrated vehicle health management *IPHM: integrated payload health management *IGHM: integrated ground health management	

Improvement Objectives

To meet the performance requirements defined within the Plug & Play model, Inspection and System Verification needs to accomplish a set of objectives. These improvements will lead to reductions in turnaround time, operational costs, and collateral damage. Table 24 summarizes the Inspection and System Verification objectives.

Table 24. Inspection and System Verification improvement objectives

- Reduce collateral damage while doing inspection.
    - Minimize damage to system from opening and entering to do the inspection – if you have to obtain access, make it easy.
    - Minimize amount of vehicle teardown to get to the data at the flight line – complete only the end-to-end tests; for turnaround, complete only end-to-end test to verify ability to fly.
- Increase confidence in inspection results.
- Increase integration with planning and scheduling activities – link to ops planning and management.
- Increase ability to determine that range and spaceport systems can accommodate the vehicle and payload.
- Reduce turnaround time.
    - Increase the time between inspections (inspection interval).
    - Decrease manual testing.
    - Decrease amount of 100% testing.
    - Minimize need for phased or depot-level inspection and maintenance.
- Reduce operational costs.
    - Minimize time on the ground.
    - Minimize number of people on the ground.
    - Reduce labor and time to perform the inspection.
    - Reduce cost to conduct inspection.
    - Reduce the level of the standing army to support.
- Increase reliability of the hardware.
    - Increase the performance margin to allow for degradation.
    - Minimize the need to just see if there is a problem (need to balance for development and operational systems).
- Increase safety in the operational environment.
    - Minimize hazardous operations.
    - Minimize the use of hazardous commodities.
    - Reduce the number of labor-intensive operations.
- Improve predictive maintenance capabilities.
- Improve nondestructive evaluation/inspection capabilities/techniques.
- Maximize the use of integrated health management systems (vehicle, payload, and ground).
- Increase focus on ground support equipment.

Operational Approaches

To accomplish the Inspection and System Verification objectives, specific operational approaches can be taken. Operational approaches focus on performing on-demand maintenance in response to and enabled by integrated health monitoring capabilities. Table 25 summarizes the operational approaches for Inspection and System Verification.

Table 25. Inspection and System Verification operational approaches

- Maintenance on demand
- Onboard sensing
- Integrated health management
    - Integrated analysis
    - Real-time data collection and analysis
    - Trend analysis
    - Intelligent analysis
- Wider abort envelop
- Phased inspection
- Integrated logistics and maintenance systems
- Predictive maintenance capabilities
- Laser imaging (MRI) for vehicle

Technology Elements

To accomplish the Inspection and System Verification objectives, specific technology elements can be developed that support the operational approaches. The goals of Inspection and System Verification are to minimize the time and resources required for this activity, to eliminate the need for duplicate tests and inspections, and to increase the probability of mission success and safety. Some of the technologies that support this TFA include enhanced simulation and simulation management capabilities, artificial intelligence, self-diagnosing/healing architectures for automated payload elements, and enhanced wireless capabilities for both terrestrial and extraterrestrial transfer of system health parameters, as well as ever-present command and control.

Novel technologies supporting inspection techniques include **real-time nonintrusive, nondestructive evaluation detectors** that are more expeditious and accurate than the current-day manual visual/physical inspections. Such detectors would include x-ray, eddy current, ultrasonics, and magnetometers. **Data management/mining techniques** will complement the real-time detectors by using enhanced mathematical modeling and artificial intelligence to process the data in a timely manner and display the evaluation conclusively. The auditing of records, in-flight data, and trending may be also augmented through the use of decision support tools to predict failure of system components and features. Advances in the arena of decision support (artificial intelligence) promise a substantial improvement in inspection capabilities. In addition to providing an inspection technique with the same capacity for examination as the more labor-intensive methods, the use of **robotics and automation** provides a method free of the bias of human inspectors, thereby offering increased consistency across inspections.

System verification is typically very labor-intensive and performed in a stand-alone environment. Technologies supporting system verification are forecasted to evolve into highly integrated systems that exhibit traits of autonomous test operations from other systems. **Self-fault isolation and repair techniques** employed in ground support equipment will ensure high availability of the infrastructure for vehicle testing. Self-healing technologies will include regenerative systems.

Table 26 summarizes the Inspection and System Verification technology elements.
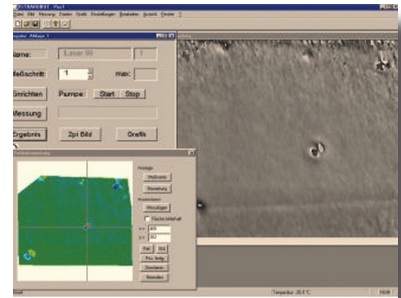
Table 26. *Inspection and System Verification technology elements*

- Automated testing and inspection
- Robotics
- Fault-tolerant systems
- SMART containers that verify integrity and environment since factory acceptance testing
- Container arrives with self-reporting status
- Self-verifying, modular interfaces
- Heads-up displays
- Nondestructive sensors
- Standardized approaches
- Self-fault isolation and repair systems
- Remote hazards detection
- Advanced imaging systems
- Noninvasive nondestructive evaluation techniques
- Stereoscopic vision helmets
- Predictive maintenance capabilities
- Integrated health management systems (vehicle, payload, and ground)
- Integrated logistics and maintenance systems
- Nonintrusive nondestructive evaluation/inspection capabilities/techniques
- Self-checking, self-healing systems and materials

Inspection and System Verification Technologies Roadmap

Figure 38 displays the major technology areas, with time-phased recommendations regarding particular technologies to pursue in improving the ability of spaceports to perform the Inspection and System Verification function.
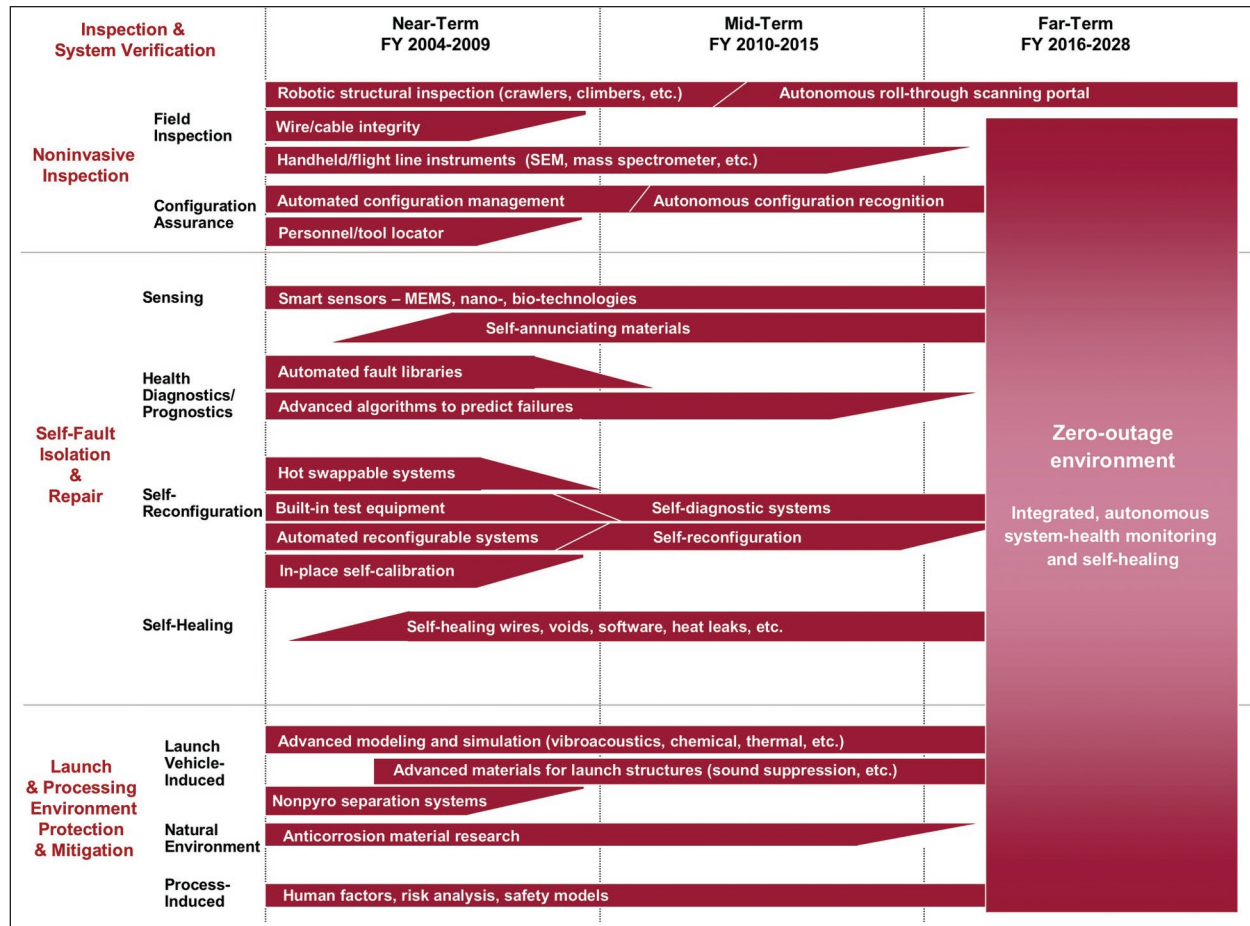
Inspection & System Verification		Near-Term FY 2004-2009	Mid-Term FY 2010-2015	Far-Term FY 2016-2028
Noninvasive Inspection	Field Inspection	Robotic structural inspection (crawlers, climbers, etc.)	Autonomous roll-through scanning portal	
		Wire/cable integrity		
		Handheld/flight line instruments (SEM, mass spectrometer, etc.)		
	Configuration Assurance	Automated configuration management	Autonomous configuration recognition	
		Personnel/tool locator		
Self-Fault Isolation & Repair	Sensing	Smart sensors – MEMS, nano-, bio-technologies		**Zero-outage environment**
		Self-annunciating materials		
	Health Diagnostics/ Prognostics	Automated fault libraries		Integrated, autonomous system-health monitoring and self-healing
		Advanced algorithms to predict failures		
	Self-Reconfiguration	Hot swappable systems		
		Built-in test equipment	Self-diagnostic systems	
		Automated reconfigurable systems	Self-reconfiguration	
		In-place self-calibration		
	Self-Healing	Self-healing wires, voids, software, heat leaks, etc.		
Launch & Processing Environment Protection & Mitigation	Launch Vehicle-Induced	Advanced modeling and simulation (vibroacoustics, chemical, thermal, etc.)		
		Advanced materials for launch structures (sound suppression, etc.)		
		Nonpyro separation systems		
	Natural Environment	Anticorrosion material research		
	Process-Induced	Human factors, risk analysis, safety models		

Figure 38. Inspection and System Verification technologies roadmap

5.5 Transportation, Handling, and Assembly

Rapid, safe, and efficient movement, relocation, precision positioning/alignment, and installation of flight/payload elements and personnel, including physically connecting, joining, or mating components, segments, or systems.
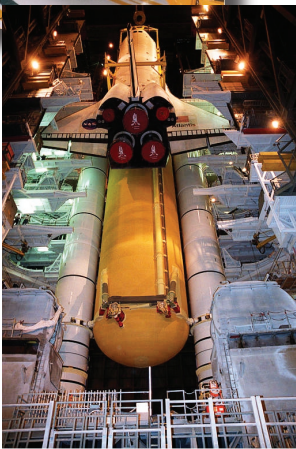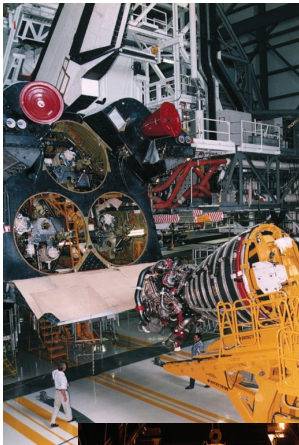
Description

Transportation is movement/relocation from one place to another. Handling is the movement within a location (e.g., lift, orientation, position, translation). Assembly is putting the parts together or joining the major elements.

Challenges

Flight hardware assembly operations today are slow because of the complex positioning, rotating, and lowering of the flight elements. These operations require highly skilled crane operators who can perform intricate maneuvers in both speed and position. In addition to the crane operators, numerous human "spotters" are required to verify proper clearance between the flight hardware and any obstruction to avoid collateral damage during assembly operations. Final assembly and closeout of the interfaces also tends to be very labor-intensive, requiring special craftsmanlike skills because of the uniqueness and complexity of the interfaces.

Transportation, Handling, and Assembly faces challenges in meeting the performance requirements associated with the Plug & Play model. Two sets of challenges exist: interfaces and movement. The interface challenges deal with the unique interfaces that each payload or vehicle uses for movement and assembly. The movement challenges deal with the intricate positioning, rotation, and handling of fragile pieces. These challenges pose specific concerns in meeting the needed performance. Table 27 summarizes these sets of challenges.

Table 27. *Transportation, Handling, and Assembly challenges*

TFA Function	Challenges

Interfaces	• Unique interfaces create the need for specialized/unique support equipment
	• Nonstandard containers and connectors
	  – Lack of standards for interfaces
	  – Multiple and unique interfaces
	  – Leads to specialized handling/testing fixtures, equipment
	  – Involves dangerous connections

Movement	• Intricate positioning, rotation, handling of flight elements
	  – Difficult and time-consuming
	  – Requires specialized equipment
	  – Requires additional maintenance and storage containers/facilities
	  – Involves suspended loads
	  – Requires breakover fixtures
	  – Creates difficulty in gaining access
	• Movement of fragile pieces to multiple, secure facilities requiring armed escorts
	• May involve movement/handling of toxic and hazardous commodities
	  – Requires clearing areas and shutting down other work
	  – Environmental issues
	  – Requires armed escorts
	• Restoring to a configuration
	• Too many movements required
	  – Too many different handling operations
	  – Requires additional training
	  – Requires additional personnel
	  – Decreases safety

Improvement Objectives

To meet the performance requirements defined within the Plug & Play model, Transportation, Handling, and Assembly needs to accomplish a set of objectives. The first set of objectives focuses on minimizing the need for transportation, handling, and assembly. The second set focuses on minimizing the need for unique GSE required to support moves. Table 28 summarizes these improvement objectives.

Table 28. *Transportation, Handling, and Assembly improvement objectives*

• Minimize need for transportation, handling, and assembly – minimize need to move items
  – Decrease amount of assembly required at spaceport and in the critical path
  – Decrease number of moves required at spaceport and in the critical path
  – Minimize number of flight elements
• Minimize need for unique GSE
  – Decrease number of different handling and transportation attach points and specialized equipment
  – Decrease number of T-0 umbilicals
  – Minimize use of unique equipment – use standard GSE interfaces
  – Minimize use of hazardous commodities and propellants
  – Maximize reusability of GSE
  – Minimize number of flight elements

Operational Approaches

To accomplish the Transportation, Handling, and Assembly objectives, specific operational approaches can be taken. Operational approaches focus on using standardized containers and transportation modes for all moves. These operational approaches are supported with the technical approaches.

Previous programs have spent significant time on transportation, alignment, connection, and interface testing that occurs during critical-path operations. The goal for Transportation, Handling, and Assembly is to expedite the movement and precision positioning of flight and payload elements while ensuring the safety of the workforce and hardware. An equally important objective is to minimize the human interfaces required and assist the workforce in accomplishing repetitive hazardous tasks such as lifting and assembly operations in a timely and safe manner. Enabling technologies include enhanced sensing and alignment, self-guiding and self-positioning systems, and robotic support for handling operations. Table 29 provides a summary of the operational approaches for Transportation, Handling, and Assembly.

*Table 29. Transportation, Handling, and Assembly operational approaches*

- Standardized, all-weather containers
- Smart, multifunction facilities and GSE
- Design guidelines for spaceports
- Standardized transportation, handling, and assembly modes
- Vehicle/payload elements are transported to staging areas on their own power
- Clamshell operations
- Factory-packaged for handling, shipping, and assembly
- Use flight attach points for transportation attach points
- Underground utilities distribution to need point
- Nonpyrotechnic separation techniques
- Standardized GSE
- Laser alignment
- Interface control drawings/documentation for vehicle/payload-to-spaceport interface
- Maximize the use of robotics and automation
- Maximize the use of integrated health management

Technology Elements

To accomplish the Transportation, Handling, and Assembly objectives, specific technology elements can be developed. The technology elements focus on the use of smart payload containers and standardized interfaces and connectors.

When flight hardware is transported, a security escort is required to ensure the safety and security of the hardware, as well as to protect the general public from large/wide loads. The escorts tend to move at a very slow pace, thus requiring significant time to transport between facilities. An investigation into the development of **advanced ground transportation systems** for flight hardware that can travel at higher speeds without endangering the hardware or the supporting workforce needs to commence. Ideally, the transportation hardware will also act as the processing stand/fixture, thus eliminating the need for additional handling operations.
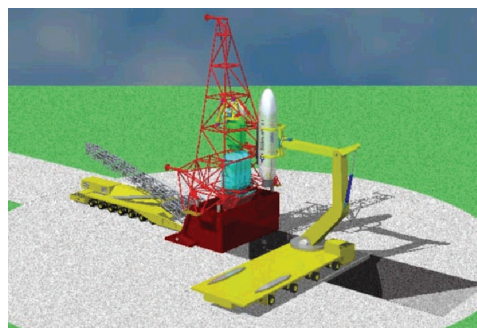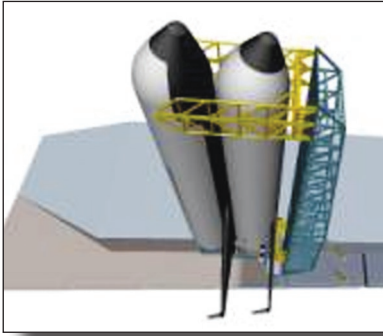
Handling fixtures today are composed of heavy steel beams or slings with little sophistication. Advanced sensing technologies can be employed in next-generation handling fixtures so the fixtures self-adjust based on the load. An example of such a system would be a **variable-center-of-gravity beam** that automatically adjusts to maintain the proper center of gravity during the lifting operation. **Robotically enhanced ground and flight hardware handling systems** can replace antiquated crane operations, improving safety and efficiency.

Assembly of flight hardware elements is a time-consuming and labor-intensive operation because of the precision positioning required. The incorporation of **robotics and automation** during lifting operations will eliminate the need for the workforce to be close to the hazardous operations. **Advanced assembly monitoring devices** such as artificial vision can also assist in precision positioning and adjustment.
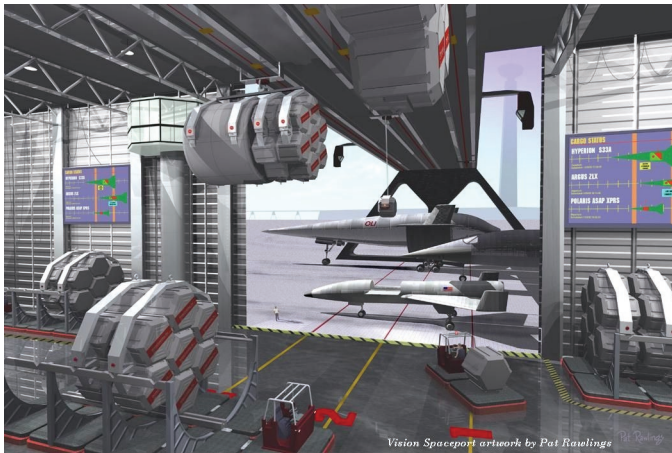
In addition to these advances, **payload containerization**, automated testing, and standardized vehicle accommodations can provide the needed capabilities of rapid transportation, handling, and assembly of payload systems. Uniformity in payload interfaces reduces risk of failures caused by system incompatibilities. If containerization techniques are adopted by the payload developers, the spaceport will have the flexibility to process diverse payload types concurrently without the need for specialized equipment, procedures, or talent.

Table 30 provides a summary of the technology elements for Transportation, Handling, and Assembly.

Table 30. Transportation, Handling, and Assembly technology elements

- Smart payload pod
  - Robust, standardized, safe class of all-weather transporters and containers
  - Provide complete environmental, vibration, and shock protection (e.g., inflatable airbags/containers)
- Multiuse facilities and GSE
- Automated umbilicals
- Modular line replaceable units
- Self-aligning systems
- Integrated health management
  - Laser alignment
  - Robotics and automation
- Standardized attach points and transportation GSE tools
- Standardized interfaces and connectors
  - Standardized and centralized
  - Modular
  - Self-verifying
  - Easy-access interfaces – equipment bay or mold line
  - Wireless
  - Quick disconnect (self-sealing and self-cleaning)
- High-strength, lightweight materials

Transportation, Handling, and Assembly Technologies Roadmap

Figure 38 displays the major technology areas with time-phased recommendations regarding particular technologies to pursue in improving the ability of spaceports to perform the Transportation, Handling, and Assembly function.
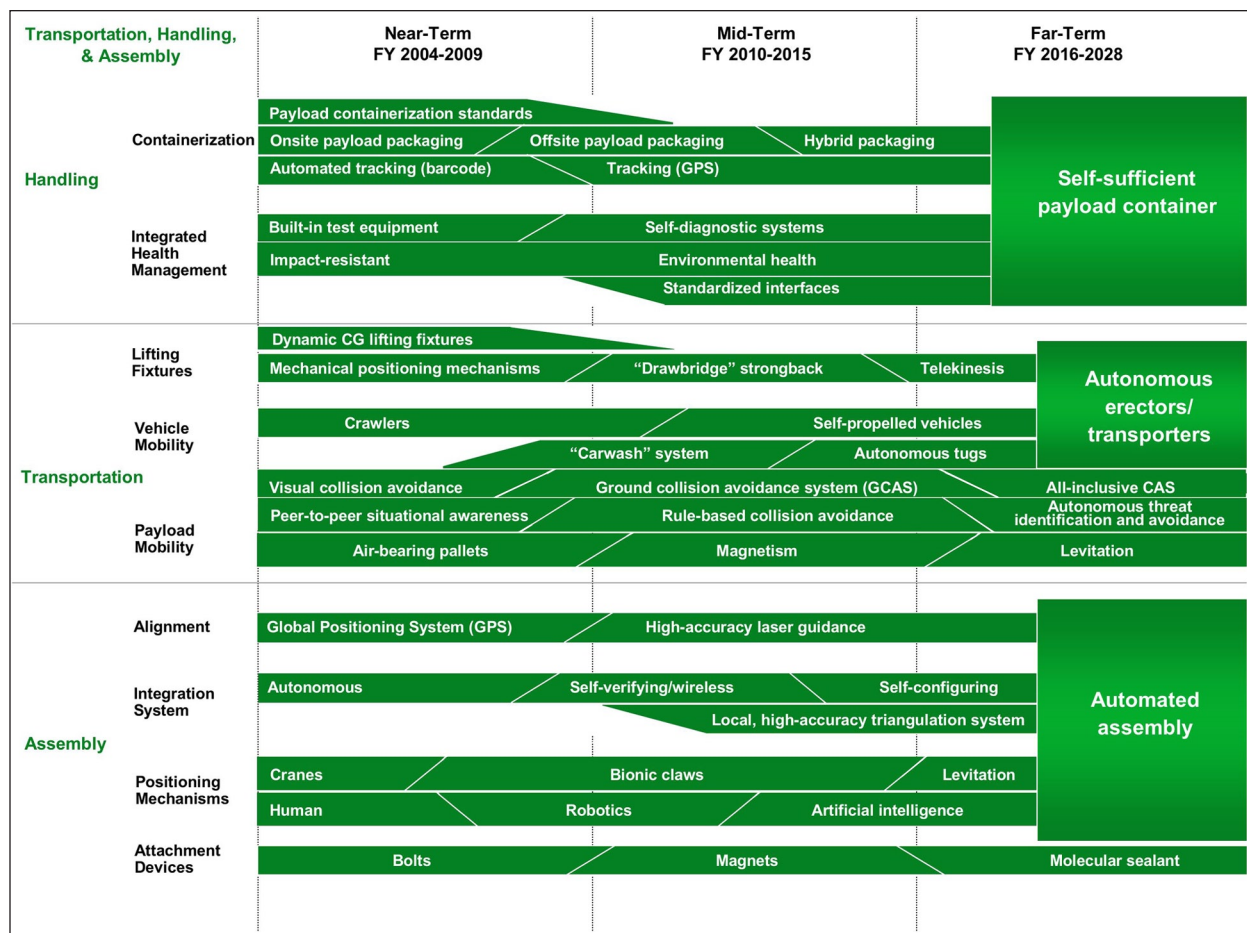

Figure 39. Transportation, Handling, and Assembly technologies roadmap

5.6 Planning/Documentation/ Analysis/Learning

Advanced information technologies for autonomous data collection (vehicle health, ground system health, work execution, configuration management), active decision support, constraint-based planning and scheduling, and financial management.

Description

The Planning/Documentation/Analysis/Learning (PDAL) technology focus area performs a critical function pertaining to management of the spaceport operations. It performs data collection, data monitoring, decision making, and reporting, as well as provides global access to spaceport information. PDAL encompasses a centralized data repository that allows for easy access to pertinent information for launch site scheduling, flow and manifest management, flight hardware loads analysis, and mission planning. The effective and efficient performance of advanced PDAL functions is vital to ensuring safe missions and reducing ground processing time and costs at the spaceport.

The **planning** phase of PDAL generates and updates resource tasking based on user requirements, identifies and schedules spaceport resources (long-term and real-time) based on schedule constraints and resource availability, monitors status of spaceport resources, and performs closed-loop monitoring of work flow. All operations performed at the spaceport must be **documented**. This includes tracking requirements, generating documentation as requirements are met, storing work/task instructions and monitoring data, collecting and providing real-time costing data, and disseminating new work instructions to equipment/workers automatically while certifying the documentation autonomously. **Analysis** must be performed to improve upon the spaceport processes. This component encompasses a comparison of actual versus planned schedules and tasks, provides improved situational awareness for process improvements, and optimizes scheduling of spaceport resources based on efficiency and safety constraints. And the most critical component of PDAL is the **learning** phase. This phase includes assessing trends associated with schedules and work performance, providing recommendations for process improvement based on the data collected, and providing the appropriate information to generate new work instructions or modify the existing work instruction to incorporate lessons learned.

Challenges

One of the costliest areas of the Space Shuttle ground operations is data processing and information management. The efficient management of information is paramount in the operation of the advanced spaceport. It is through the timely availability of relevant information that efficiencies in scheduling and tasking are optimized. However, providing for those efficiencies is not an end unto itself but the beginning of the process to improve operational parameters in tasking through analysis and learning. Furthermore, it is through the efficient and effective management of information that costs may be reduced. Specifically, the timely availability of information allows for rapid and effective reaction of the business enterprise, as well as the adaptation of technical systems to changes in the operational environment.

Planning is founded upon previously gained knowledge and expertise that is applied to the current challenge toward a successful outcome. This knowledge may be derived from learning, rote memorization or experience, or the analysis of external data. Therefore, the planning of advanced spaceport operations is reliant upon the documentation of past operations, analysis of operational conditions and environment, and the learning of improved traits toward increased efficiencies.

PDAL faces challenges in meeting the performance requirements associated with the Plug & Play model. Two sets of challenges exist: the diversity of approaches for handing the information and the labor-intensive process of planning, documentation, analysis, and learning. Table 31 provides a summary of the challenges facing PDAL.

Table 31. Planning/Documentation/Analysis/Learning challenges

- Diversity of approaches for:
  - Procedures and paperwork
  - Data formats
  - Long, numerous, conflicting checklists
- Leads to nonstandard, slow, paper-based, lengthy review/approval and labor-intensive methods that rely on workers' craftsmanship for:
  - Analyzing records for off-nominal conditions
  - Capturing lessons learned
  - Configuration control
  - Checklist management
  - Determining out-of-family issues
  - Analyzing trends

Improvement Objectives

To meet the performance requirements defined within the Plug & Play model, PDAL needs to accomplish several sets of objectives. The first set focuses on supporting a flight rate, the second on creating shared information sources across the spaceport, the third on improving the decision-making ability, and the fourth on improving the PDAL systems. Table 32 summarizes these improvement objectives.

Table 32. Planning/Documentation/Analysis/Learning improvement objectives

- Enable a highly efficient, responsive, and safe spaceport that maximizes flight rate.
    - Reduce scrubs caused by spaceport issues/conflicts.
    - Minimize accidents (need to capture safety aim).
    - Optimize use of resources (human, facility, financial, etc.) (also leads to process improvement).
    - Automate processes.
- Create shared information sources to support planning, analysis, and work execution.
    - Enables global access for dynamic operations planning, scheduling, execution, improvement, and conflict detection/resolution.
- Improve decision making through collaboration.
    - Provide safe, fair, and equitable access to spaceport resources.
    - Improve situational awareness and state management (ties to shared information sources).
    - Improve decision support systems.
    - Coordinate support with local, regional, and other entities (emergency authorities, spaceports, range, etc.).
- Improve the PDAL systems
    - Make data formats and work instruction formats more consistent.
    - Collect and analyze data and information faster.
    - Analyze more data in real time.
- Minimize maintenance downtime and support costs created by logistics issues.
    - Eliminate or minimize preventive maintenance and calibration requirements.
    - Eliminate known maintenance problems in similar systems.

Operational Approaches

To accomplish these PDAL objectives, specific operational approaches can be taken. Operational approaches focus on using standard, paperless systems and processes in a cafeteria plan for spaceport services. These operational approaches are supported with the technical approaches. Table 33 provides a summary of the PDAL operational approaches.

Table 33. Planning/Documentation/Analysis/Learning operational approaches

- Standard, paperless system for:
    - Document generation and approval
    - Automated plan generation, deconfliction, scheduling, and approval
    - Automated, intelligent processing
    - Complete records of off-nominal conditions
    - Automated trend analysis
    - Autonomous configuration management
- Standardized processes
- Cafeteria plan for spaceport services

Technology Elements

To accomplish the PDAL objectives, specific technology elements can be developed that focus on using automated planning and work control systems.

Improved documentation processes and capabilities are pivotal to the success of the spaceport organization. The ability to gather and store data in forms that accommodate the needs of the user base is critical as the basis for learning and analysis and, ultimately, as the guidance for operational planning updates. Critical technologies to respond to these serious needs include the development of **advanced information technologies** for autonomous data collection (e.g., vehicle health, ground system health, work execution, configuration management, task and resource scheduling, and agent-based data retrieval), **active decision support**, and **constraint-based planning and scheduling**. These capabilities will provide for the efficient and effective integration of data into the operational schema that will significantly reduce the recurring costs of ground processing.

Improved technologies offer the catalyst toward increased efficiencies by providing the appropriate dissemination and control of strategic data. A spaceportwide integrated requirements management system can generate, delete, add, and track (or perform closed-loop accounting) of requirements and configuration, requirements change processing, logistics interfaces, maintenance planning, cost support, validation, and transactions – delivery and processing. In conjunction with the integrated resource management system, an automated resource management and integrated work execution system can perform all of the spaceport planning and scheduling for both near-term and long-term operations and missions. General work control and execution functions will capture the actual task duration for later comparison to scheduled duration. Improvements in **artificial reasoning**, **task and resource management**, and **data extraction** (the distinction of tactically significant information from the continual influx of data) provide the cornerstone for the advanced spaceport. By ubiquitously and autonomously gathering and processing data, we will make vital and relevant information available for immediate response and long-range planning and development without the need for intricate system management schemes.

The timely, accurate analysis of system or artifact parameters is required to provide the basis for safety of flight decisions and mission planning, as well as accurate launch planning in the global space community. Analysis of vehicle/payload physical, electrical, and resource characteristics demonstrates the particular system's ability to support the intended mission without compromise of mission effectiveness or public safety. In addition, degrees of fiduciary responsibility and accounting, regulatory compliance, process improvement, and business administration remain important measures of spaceport success and ultimate commercial viability.

Analysis technologies pivotal to the maturation of the spaceport enterprise include those associated with modeling and simulations, life cycle engineering, and closed-loop accounting of mission/system requirements and records. Specific technologies such as **semantic and neural networking**, **configuration management techniques**, and task forensics continue to lead the evolution into the era of the integrated spaceport architecture.

Learning is the act of assimilating appropriate data into a manageable knowledge package for the purpose of influencing future activities. Although this act most readily relates to the human element, it is also applicable to support services provided by many technologies. Temporally correct multimedia services for the storage and recall of events and artificial intelligence systems that provide the inference between previous work techniques and proposed modifications to those techniques offer the technical vehicles for transforming today's discoveries into tomorrow's knowledge. New technologies that enhance human performance through state-of-the art training tools can provide the basis for learning in a relevant environment. Accurate modeling and simulation of launch processing situations provide a unique perspective to the trainee. Simulation should include the ability to model entire multivehicle missions, detailed processing activities, facility and workforce resources, and the effects of work interruptions caused by hazardous activities. This modeling capability is essential for assessing the impacts of vehicle design on operations and developing processes for efficient and safe operations, facilities, and ground support system designs.

To create these virtual training systems, one must collect relevant information from procedures, requirements, configuration, etc., in a form compatible with the simulation programs and computer systems and that can be readily searched and analyzed to identify trends and aid in process design operations. Process and operations data can also be collected to simulate operations for training purposes. This capability can be used to modify and evaluate operations and to perform trade studies.

Table 34 provides a summary of the PDAL technology elements.

Table 34. Planning/Documentation/Analysis/Learning technology elements

- Standard documentation methods/formats
- Shared data storage structure
- Data acquisition (dynamic acquisition/processing could avoid data mining)
- Automated documentation certification
- Dynamic scheduling, tracking, and planning
- Heads-up display of procedures
- Integrated health management
- Automated, responsive, dynamic requirements management
- Simulation models for preplanning
- Automated decision models
- Data warehousing
- Electronic approvals
- Risk management intelligence
- Data compression
- Automated debrief systems
- Expert systems/artificial intelligence
- Decision analysis aids and tools
- Safety and hazard management analysis tools

Planning/Documentation/Analysis/Learning Technologies Roadmap

Figure 39 displays the major technology areas, with time-phased recommendations regarding particular technologies to pursue in improving the ability of spaceports to perform the Planning/Documentation/Analysis/Learning function.
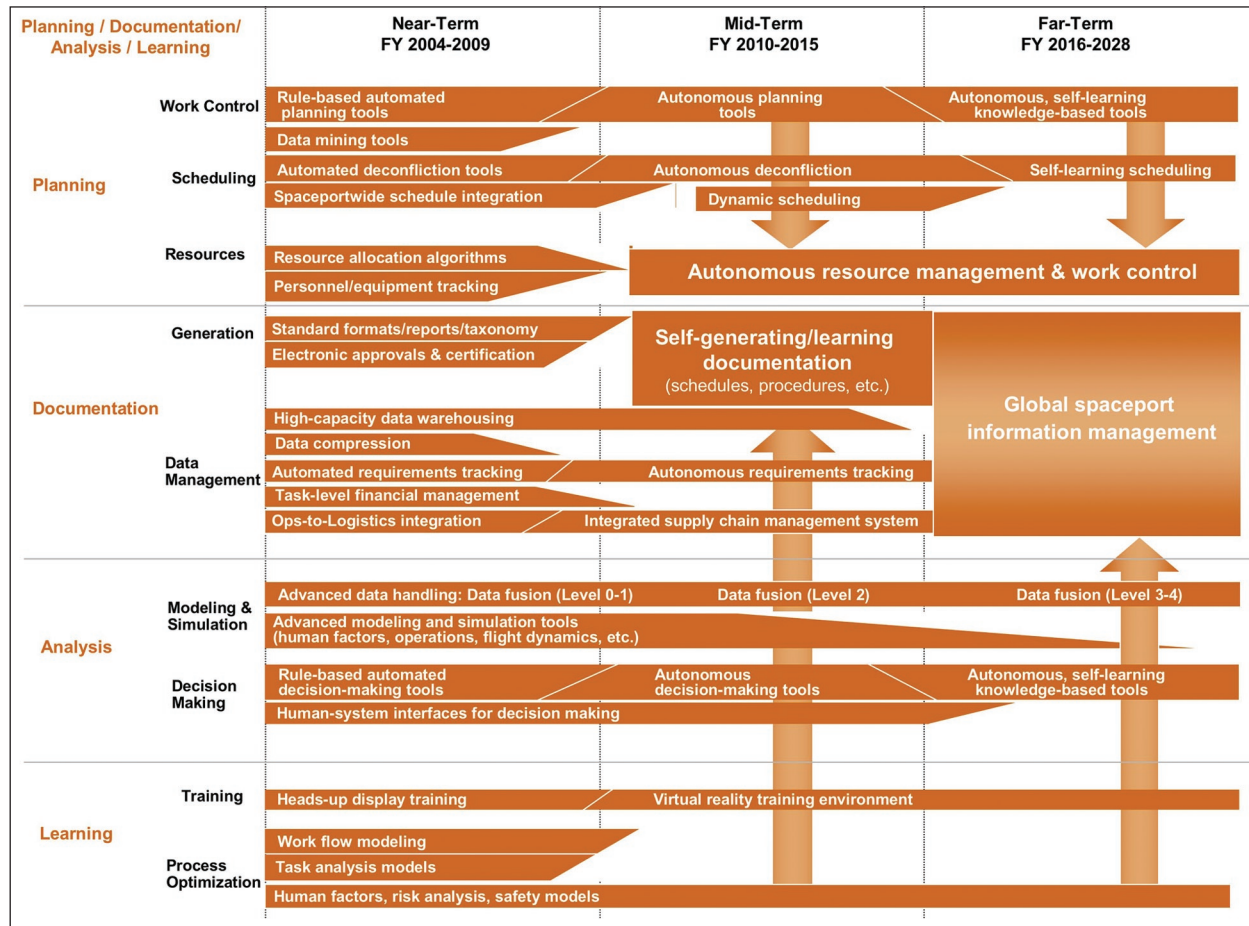
Figure 40. Planning/Documentation/Analysis/Learning technologies roadmap

5.7 What comprehensive technology elements are needed to realize the Plug & Play vision?

An extensive number of key technologies contribute to the Plug & Play vision of providing low-cost, routine, safe access to space. Of this large set of technologies, many cross technology focus areas and apply to disciplines other than space access. Some technologies will be government-unique or not commercially available. It then becomes the responsibility of the federal government to develop these technologies to enable the overall vision.

Figure 41 highlights the key technologies that will foster the standardized yet flexible spaceport architecture of the future. This roadmap is not intended to be all-inclusive but rather to document the enhancing and enabling technologies for pursuit of development. The Command, Control and Monitoring technologies and the Planning/Documentation/ Analysis/Learning technologies have been combined because of their similar elements. The follow-on ASTWG technology plan will address these two TFAs as one.

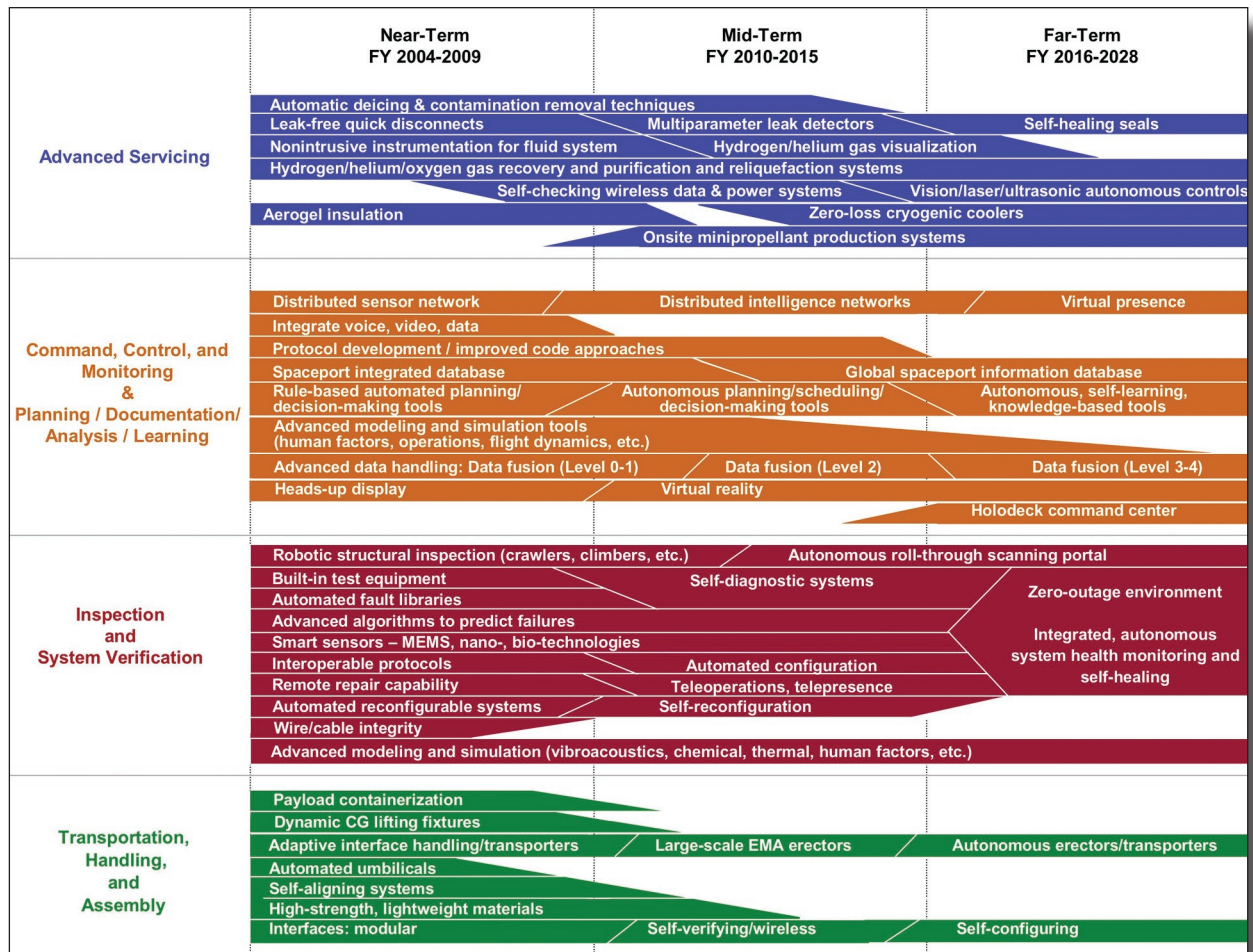|	Near-Term FY 2004-2009	Mid-Term FY 2010-2015	Far-Term FY 2016-2028
Advanced Servicing	Automatic deicing & contamination removal techniques Leak-free quick disconnects Nonintrusive instrumentation for fluid system Hydrogen/helium/oxygen gas recovery and purification and reliquefaction systems Aerogel insulation	Multiparameter leak detectors Hydrogen/helium gas visualization Self-checking wireless data & power systems Zero-loss cryogenic coolers Onsite minipropellant production systems	Self-healing seals Vision/laser/ultrasonic autonomous controls
Command, Control, and Monitoring & Planning / Documentation/ Analysis / Learning	Distributed sensor network Integrate voice, video, data Protocol development / improved code approaches Spaceport integrated database Rule-based automated planning/ decision-making tools Advanced modeling and simulation tools (human factors, operations, flight dynamics, etc.) Advanced data handling: Data fusion (Level 0-1) Heads-up display	Distributed intelligence networks Autonomous planning/scheduling/ decision-making tools Data fusion (Level 2) Virtual reality	Virtual presence Global spaceport information database Autonomous, self-learning, knowledge-based tools Data fusion (Level 3-4) Holodeck command center
Inspection and System Verification	Robotic structural inspection (crawlers, climbers, etc.) Built-in test equipment Automated fault libraries Advanced algorithms to predict failures Smart sensors – MEMS, nano-, bio-technologies Interoperable protocols Remote repair capability Automated reconfigurable systems Wire/cable integrity Advanced modeling and simulation (vibroacoustics, chemical, thermal, human factors, etc.)	Autonomous roll-through scanning portal Self-diagnostic systems Automated configuration Teleoperations, telepresence Self-reconfiguration	Zero-outage environment Integrated, autonomous system health monitoring and self-healing
Transportation, Handling, and Assembly	Payload containerization Dynamic CG lifting fixtures Adaptive interface handling/transporters Automated umbilicals Self-aligning systems High-strength, lightweight materials Interfaces: modular	Large-scale EMA erectors Self-verifying/wireless	Autonomous erectors/transporters Self-configuring

Figure 41. Technology roadmap for Plug & Play